

A life cycle assessment case study of ground rubber production from scrap tires

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Abstract

Purpose The number of scrap tires generated in China has grown dramatically every year. Generation of ground rubber from scrap tires is the dominant management option in China. It is necessary to assess the environmental impacts of ground rubber production from scrap tires to provide technical advices on a cleaner production.

Methods Production of ground rubber from recycled scrap tires consist of three steps: rubber powder preparation, devulcanization, and refining. A process life cycle assessment (LCA) of ground rubber production from scrap tires is carried out, and Eco-indicator 99 method coupled with ecoinvent database is applied to evaluate the environmental impacts of this process.

Results and discussion During the ground rubber production stage, the impact factor of respiratory inorganic is the most serious one. Devulcanization has the highest environmental load of about 66.2 %. Moreover, improvement on the flue gas treatment contributes to a cleaner production and a more environmental-friendly process. Applying clean energy can largely reduce environmental load by about 21.5 %.

Conclusions The results can be a guidance to reduce environmental load when producing ground rubber from scrap tires. Meanwhile, increasing energy efficiency, improving

environmental protection equipment, and applying clean energy are the effective measures to achieve this goal.

Keywords Cleaner production · Eco-indicator 99 · Environmental load · Ground rubber · LCA · Scrap tire

1 Introduction

The number of scrap tires generated in China has grown dramatically every year due to the increasing use of automobiles. During 2001 to 2006, the number of used tires was increased by 15–20 % per year, from 50 million to 150 million (Li et al. 2010; Liu 2008). According to the surveys, there were 225 million of tires in use in 2011, generating 250 million scrap tires.

Disposal of scrap tires has become a serious problem since it is illegal to send scrap tires to landfill (Corti and Lombardi 2004; RafiqueRMU 2012) in Europe. In China, there is still lack of legislation on scrap tire disposal. However, landfill of scrap tires has raised a lot of public concerns and becomes a less attractive option. Reclaimed scrap tires can be combusted for energy recovery or reprocessed for material recycling (Feraldi et al. 2013). In the USA, scrap tires are mainly utilized as tire-derived fuel for energy recovery followed by ground rubber production and civil engineering applications (Fiksel et al. 2009; Franklin 2010). Ground rubber production is the primary application of scrap tires in China due to the shortage of natural rubber resources (Jin et al. 2009; Li et al. 2010). Moreover, it received energetic support from the National Development and Reform Commission (NDRC) in the 12th 5-year plan (National Development and Reform Commission 2012). Ground rubber is of high value that can be used as raw materials for many products (Lloyd 2004). However, its production releases harmful chemicals and requires extensive energy consumption, making it a less advantageous option

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for waste management from an environmental protection perspective (Li et al. 2003). Hence, it is crucial to assess the environmental impacts of ground rubber production using scrap tires to provide valuable advices on technical innovation for a cleaner production.

Life cycle assessment (LCA) is considered as an efficient and comprehensive tool to evaluate the environmental impacts of a product throughout its life cycle, starting with the extraction and processing of raw materials, manufacturing and production, product transportation, use and maintenance, until its waste disposal (Corominas et al. 2013; Gerber et al. 2013; Heijungs et al. 2013; Liu et al. 2013; Van Goethem et al. 2013). Clauzade et al. (2010) carried out a comprehensive LCA study of nine recovery methods for end-of-life tires (Lecouls and Klöpffer 2010). The study shows that productions of synthetic turf and molded objects own the most significant environmental benefit. It is worth noting that synthetic turf and molded objects are often made from ground rubber. No literature has been published on the process LCA of ground rubber production from scrap tires to investigate each step, respectively, for clean production. Hence, this study aims to provide a comprehensive process LCA study on ground rubber production from scrap tires in China and to investigate the environmental load of each subprocess. Also, the following aspects will be taken into consideration and further discussed: (1) What environmental impacts are caused during the ground rubber production from scrap tires; (2) which step causes the most significant adverse environmental impacts; (3) what is the influence of this process on ecosystem quality, human health, and resources; and (4) how could we make the ground rubber production process more environment friendly.

2 Methods

2.1 Goal and scope definition

According to ISO 14040 (2006) and ISO 14044 (2006), LCA method includes four steps: (1) goal and scope definition; (2) life cycle inventory (LCI) analysis; (3) life cycle impact assessment (LCIA); and (4) interpretation (Curran 2013; Klöpffer 2012). Goal and scope definition includes the reason for executing LCA, goal of the LCA, the description of system boundaries, and the functional unit (Finnveden et al. 2009).

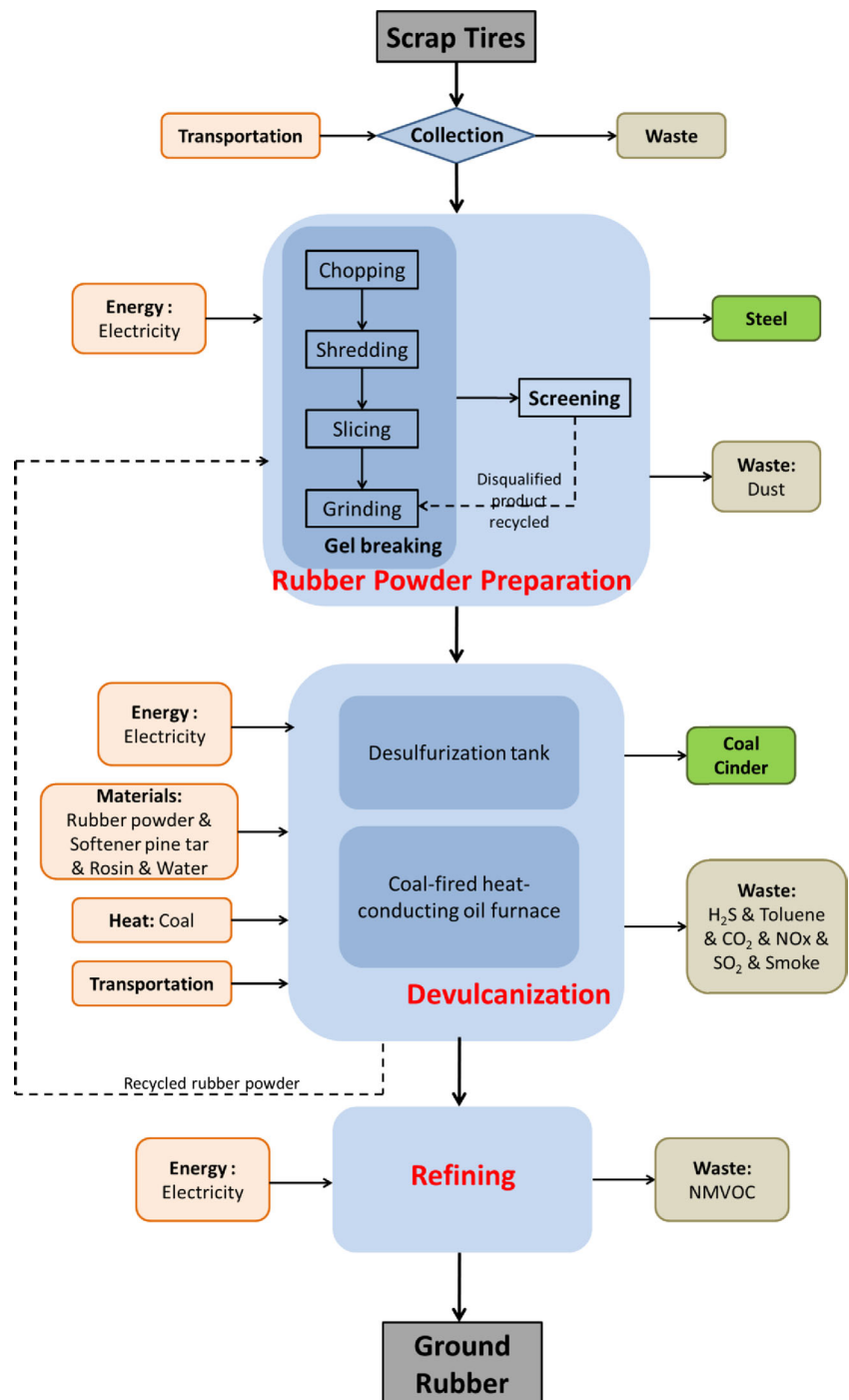
The goal of this study is to analyze the environmental impacts of ground rubber production process from scrap tires in China. Production of ground rubber is a complex process that could be divided into three steps: rubber powder preparation, devulcanization, and refining. First, the scrap tires are pulverized into a fine powder with a particle size of 30 mesh. Meanwhile, the steel fraction from scrap tires is removed and recycled for further use. A fan with gas collection efficiency of 90 % and dust removal efficiency of 95 % is applied in this

step. The second step is the devulcanization process in a desulfurization tank. Plasticizers named pine tar and rosin are added proportionally to improve plasticity of rubber powder that was obtained from step one. Pine tar is a viscous liquid or semisolid made from pine through destruction and distillation. The main components of pine tar are guaiacol, cresol, methyl cresol, phenol, o-ethyl phenol, turpentine, etc. Rosin is solid with color ranging from yellowish to brown. It is made from the oil flowed from pine trunk. Rosin is mostly applied as flux when welding electronic circuit or scouring musical instrument for good music. A coal-fired oil furnace is applied to keep the desulfurization tank at a high temperature of 503 K under the pressure of 2.2 MPa. There are two strands of waste gas discharged in the step. One is discharged from desulfurization tank, and the main contaminants are hydrogen sulfide (H_2S) and toluene. A patented cycle absorption separator (ZL02 2 84546.1 patent. Jiangxi Guoyan Rubber Company Limited 2003) is utilized to treat the waste gas. First, waste gas is cooled and decompressed twice in two heat exchangers by circulated cooling water. Then, a gas absorber using sodium carbonate solution as absorbent is applied to remove the contaminants in the gas stream, achieving a removal rate of 99 %. At last, the treated gas enters into the coal-fired heat conduction oil furnace to be incinerated. The other gas stream is discharged from coal-fired heat conduction oil furnace and mainly consists of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and smoke. According to Emission Standards of GB 13271–2001 (GB 13271–2001 2001) in China, emitted dust concentration in the flues gas should be less than or equal to 200 mg/m^3 and SO_2 emission concentration should be less than or equal to 900 mg/m^3 . A device equipped with wet flue gas desulfurizer and filter is used to treat the flue gas with a dust collection efficiency of 96 % and desulfurization efficiency of 75 %. Meanwhile, the efficiency on NO_x removal is about 15 %. During the refining stage, rubber from devulcanization process is reprocessed into rubber plate. Additionally, nonmethane volatile organic compounds are collected by a gas-collecting hood and then absorbed by activated carbon with a removal efficiency of 80 % before being released to the atmosphere.

A detailed block diagram for the current LCA system is shown in Fig. 1. Each of the blocks shown in Fig. 1 consists of energy and materials as input and emissions or by-products as output. Current study considers the unit process of scrap tire collection and ground rubber production as described above. In China, collectors of scrap tires cooperate with tire retailers, garages, or individuals who offer the used tires for a door-to-door collection service (Li et al. 2010). Hence, collection of scrap tires involves the calculation of the distances and fuel consumption for transport waste to factory. After investigation, the transportation radius is set as 100 km.

The construction of building or the manufacture of machines, transport trucks are not considered (Clauzade et al.

Fig. 1 The scope of ground rubber production. The *black boxes* refer to scrap tires or finished product; the *blue boxes* refer to the main steps involved during the ground rubber production; the *red boxes* refer to materials or energy inputs to system; the *green boxes* refer to coproductions; the *gray boxes* refer to waste emission to nature; the *solid arrows* refer to the materials and energy flows; the *dashed arrows* refer to recycled energy flows



2010). Also, noise will not be considered. Noise mainly comes from production equipment and fans, which is lower than 65 dB (A) after shock-absorbing and soundproofing. In this case, only people who work in the neighborhood will be affected, and they normally wear ear protection equipment from noise damages. Hence, noise is negligible compared to other environmental impacts in this case. During rubber powder preparation, low-alloyed steel is separated and recycled. The type of steel is named as Q345 based on the national

standard of GB/T 1591–1994 in China (GB/T 1591–1994 1994). Considering that most steel are already produced from recycled scrap (Pauliuk et al. 2012), the recycling of steel is not taken into account in this work.

Recycled rubber powder and coal cinder are recycled as by-products. Hence, the benefits from reuse of these materials will be considered (Clauzade et al. 2010). Coal cinder is reused for other applications while recycled rubber powder is reused in the step of rubber powder preparation. Impacts on

the utilization of ground rubber will not be taken into consideration for avoiding complexity and confusion since this study only aims to assess its production process from scrap tires.

2.2 Functional unit

This study aims to assess a process life cycle of ground rubber production from scrap tires. A detailed description of the typical process is needed. After a comprehensive survey, FH Rubber and Plastic Regeneration Company (FH Company) was identified and selected as a representative of ground rubber production industry in Zhejiang province, China. The annual production capacity of FH Company has been 20,000 t since 2011. The annual production of FH Company is defined as the functional unit that is 20,000 t of ground rubber.

2.3 Eco-indicator method

Eco-indicator method is widely applied in many LCA studies by Huntzinger and Eatmon (2009), Yusoff and Hansen (2007), and others (Li et al. 2010; Song et al. 2013). Eleven impact categories are taken into account in Eco-indicator 99 method, including carcinogens, respiratory organics, respiratory inorganic, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels. However, noise is not considered in Eco-indicator 99 method. Fortunately, noise is a very insignificant environmental impact factor that can be neglected in this study. Moreover, Eco-indicator 99 is a damage-oriented approach. Characterization factors are calculated at midpoint level. Then, the impact category indicator results obtained from the characterization step are added to form damage categories. Normalization is performed at damage category level (endpoint level in ISO terminology). The 11 environmental impact categories are then classified into three damage categories: (1) human health, (2) ecosystem quality, and (3) resources. In the hierarchist (H) perspective of Eco-indicator 99, the chosen time is long term, and environmental impacts of substances involved are taken into consideration if there is consensus regarding their effect. Hence, the Eco-indicator 99 (H) is a suitable approach to assess the life cycle environmental impacts of ground rubber production in China.

2.4 Life cycle inventory analysis

LCI is a phase to list all the data collected and identify inputs/outputs (Li et al. 2010). The foreground data were collected from the following five sources:

- (1) Quantities of materials and energy inputs were collected from the actual production process of FH Company.

- (2) Emission data were obtained from the Environmental Impact Assessment (EIA) report of FH Company.
- (3) To ensure an accurate calculation, the obtained data on emission were compared with the benchmark in the First Pollution Source Census (FNPSC) by Ministry of Environmental Protection of the People's Republic of China (2010).
- (4) Also, data on waste gas emission, especially from coal-fired heat conduction oil furnace, were compared with those from peer industry (Chen et al. 2010; National Development and Reform Commission 2012).
- (5) Last, a survey in FH Company is carried out to find the “missing” emission data that are not contained in the EIA report of FH Company.

The detailed foreground data of this LCA study are summarized in Table 1. Numbers are referred as the data source as described above. The inventory is divided into three sections corresponding with the three steps of production process. Each section contains materials and energy input and products and waste output.

Moreover, ecoinvent database was applied in this study to provide detailed background data on generic materials, energy, transportation, and waste. Coal cinder is output as coproduct. It is often recycled for producing cement, brick, and other fire-proof materials. Hence, the record used for material replaced by the recovery of coal cinder is “refractory, fireclay, packed, at plant/kg/DE” in ecoinvent database, refer from Kellenberger et al. (2007). Data for the electricity input is the record in ecoinvent as “electricity, high voltage, at grid/CN U.” It regards high-voltage supply mix as identical to production mix at high-voltage grid (Frischknecht et al. 2007). Since the needed tonnage of transportation is different, the transportation record (Spielmann et al. 2007) of scrap tires is “transport, lorry >32 t, EURO4/RER U.” The transportation record of rosin is “transport, lorry 16–32 t, EURO4/RER U,” and the transportation record of pine tar is “transport, lorry 7.5–16 t, EURO4/RER U.” It is worth mentioning that ecoinvent database is more adapted to Western European cases and some materials used in Chinese industries cannot be found in these databases. For instance, pine tar is used as softener during the devulcanization step in China, and no relevant information was found in the base case. Hence, a simplified LCA was carried out to assess the environmental impacts of pine tar based on a report from a pine tar production company. The main annual inputs of 200 t ones of pine tar production are 645.8 t of water, 0.027 t of fuel oil, 160 m³ of natural gas, and 31.7 thousand kWh of electricity while the main annual outputs are 106.2 t of waste water and 57.8 t of solid waste. The record of “resin size, at plant/RER U” is applied for rosin as a plasticizer (Hischier 2007).

Table 1 The inventory of the LCA of processing ground rubber

Step	Unit	Value	Materials and energy	Data sources ^a
Rubber powder preparation				
Input	t	12,000	Scrap tires	(1)
	tkm	1,200,000	Transportation	(5)
	kWh	500,000	Electricity	(5)
Output	t	2,200	Steel	(2)
	t	3.944	Dust	(2)
Intermediate product	t	9,800	Rubber powder	(1)
Devulcanization				
Intermediate product	t	9,800	Rubber powder	(1)
Input	t	9,800	Purchased rubber powder	(1)
	t	200	Pine tar	New made LCA
	tkm	120,000	Transportation of pine tar	(5)
	t	200	Rosin	(1)
	tkm	60,000	Transportation of rosin	(5)
	t	200	Water	(1)
	kWh	616,500	Electricity	(4) (5)
	MJ	90,000,000	Coal	(1)
	t	200	Recycled rubber powder	(2)
	t	900	Coal cinder	(2)
	t	0	Hydrogen sulfide (H ₂ S)	(2)
	t	0	Toluene ^b	(2)
	t	7,500	Carbon dioxide (CO ₂)	(4) (5)
Output	t	14	Nitrogen oxides (NO _x)	(5)
	t	9	Sulfur dioxide (SO ₂)	(5)
	t	33	Smoke	(3) (5)
	t	20,000	Devulcanized rubber powder	(1)
Refining				
Intermediate product	t	20,000	Devulcanized rubber powder	(1)
Input	kWh	4,816,500	Electricity	(5)
Output	t	20,000	Ground rubber	(2)
	t	0.74	Nonmethane volatile organic compounds (NMVOCs)	(2)

^a The numbers refer to the five sources mentioned in the above in Sect. 2.4

^b Means toluene equivalence converted to the VOCs in this process

3 Results and discussion

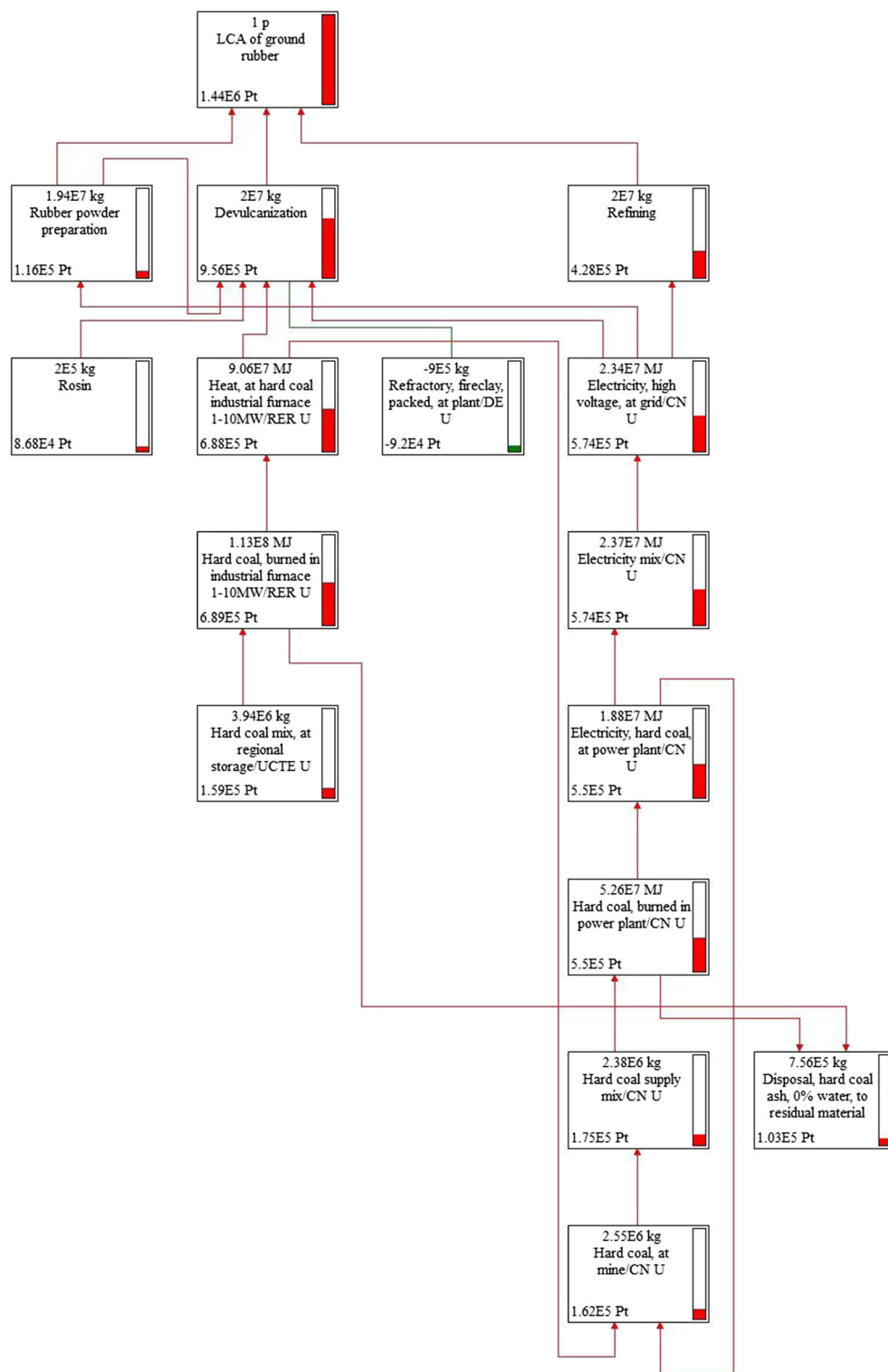
3.1 Life cycle impact assessment

The network of the LCA of ground rubber production process is shown in Fig. 2. The unit point (Pt) is applied to describe the comprehensive ecological index point. Positive values represent harmful environmental impacts while negative values represent beneficial environmental impacts. The bigger the number is, the larger environmental impacts it poses. The life cycle of ground rubber consisted of three steps as showing in the second line: The first step is rubber powder preparation which shows the least value of 8.06 % on environment. The second step is devulcanization that owns the most significant

value of 66.2 %. However, it is worth mentioning that the recycling of coal cinder shows a negative value, indicating a positive effect on the environment. Refining also has a positive value of 29.7 %, which is mainly contributed from electricity consumption.

ISO 14042 provides a step-by-step procedure that includes characterization and normalization for the materials and emission input/output in the inventory analysis. Figure 3 shows the 11 environmental impacts after executing characterization and normalization steps. Due to the recycling of coal cinder, some environmental impacts are offset and devulcanization even shows a beneficial effect on ozone layer. As to other impact categories, the three steps all do harm to them. Respiratory inorganic is the most affected category in the whole process,

Fig. 2 The network of the LCA of ground rubber. *Red arrows* refer to materials and emissions that are harmful to the environment; *green arrows* indicate a beneficial effect of the materials in the box on environmental; the *red thermometers* in each box refer to the contribution of each step to the total score of the process

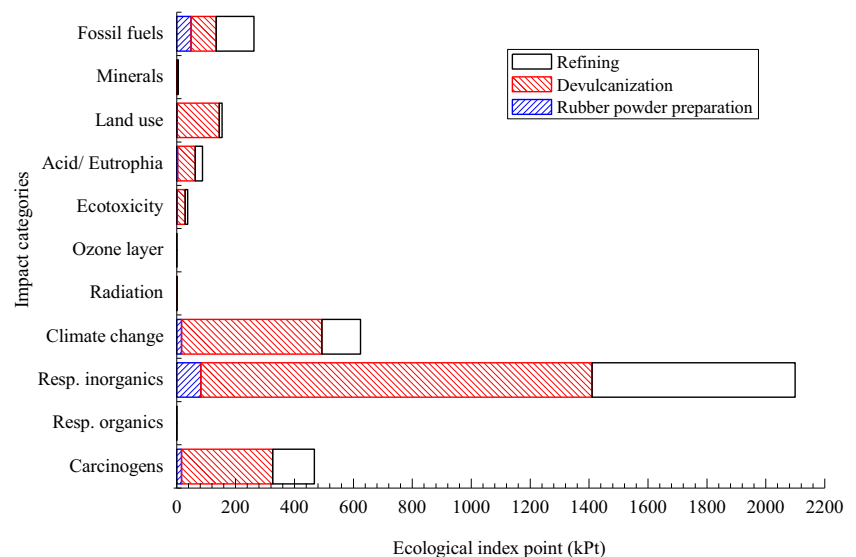
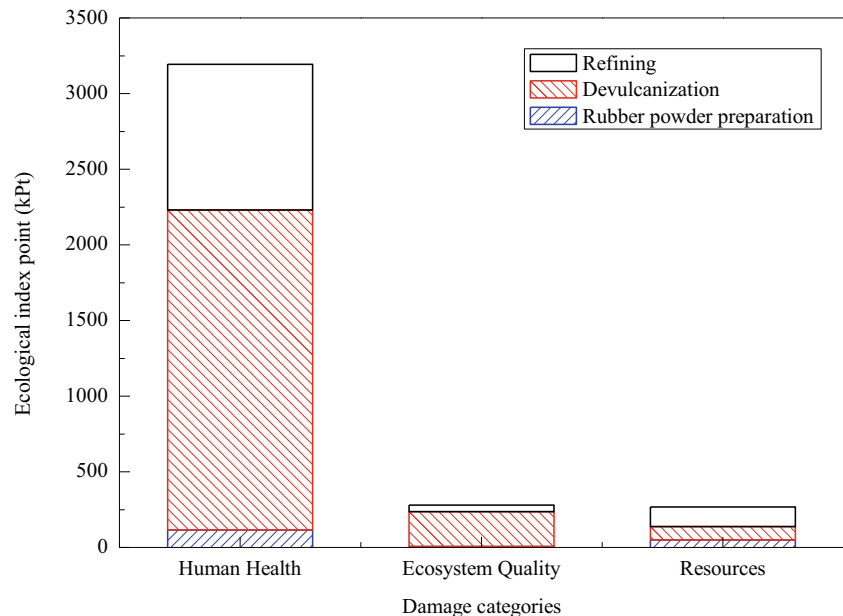


followed by climate change, carcinogens, and fossil fuels. In terms of each step, the three steps all have the most negative impact on respiratory inorganic.

Three damage categories, including human health, then ecosystem quality and resource, are shown in Fig. 4.

3.2 Interpretation and advices

Devulcanization has the highest environmental load since desulfurization requires extensive heat from a large amount of coal combustion, resulting in emissions of SO_2 , NO_x , CO_2 ,

Fig. 3 Normalization of processing ground rubber at impact category level**Fig. 4** Normalization of processing ground rubber at damage category level

and dust. This is also the reason why respiratory inorganic has the biggest value in the 11 impact categories and human health is the most noticeable damage. Similar reason can be applied to explain the impact value of refining step. Briefly speaking, the most serious damage comes from coal combustion.

To meet the environmental standard, FH Company has already utilized gas treatment equipments in process. However, during devulcanization stage, the desulfurization efficiency is 75 %, while the efficiency on NO_x removal is only 15 %. To achieve a stricter emission standard, a more advanced gas treatment technology is selected and set as reference scenario 1. Selective non-catalytic reduction of NO_x is chosen to achieve a removal efficiency of 50 % (Shin et al. 2007; Yang et al. 2011). Meanwhile, the desulfurization efficiency is increased to 95 % by using wet desulfurization technique (Ding

et al. 2014). However, further investigation needs to be done on the environmental load of the more advanced gas treatment technology employed under this scenario since 25 % ammonia is added as input. Hence, a new LCA study was carried out on the reference scenario, and the inventory is listed in Table 2.

Table 2 The inventory of system with high waste gas disposal efficiency scenario

Step	Unit	Value	Materials and energy	Data sources
Devulcanization				
Input	t	8.5	25 % ammonia	(Shin et al. 2007)
Output	kg	2.33	SO_2	(Ding et al. 2014)
	t	8.25	NO_x	(Shin et al. 2007)

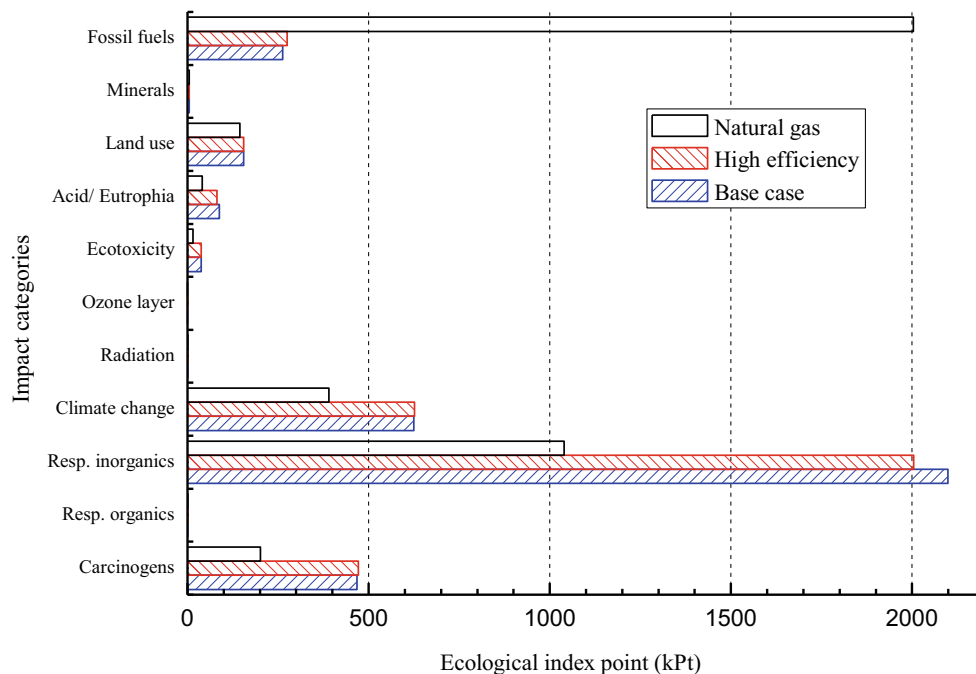
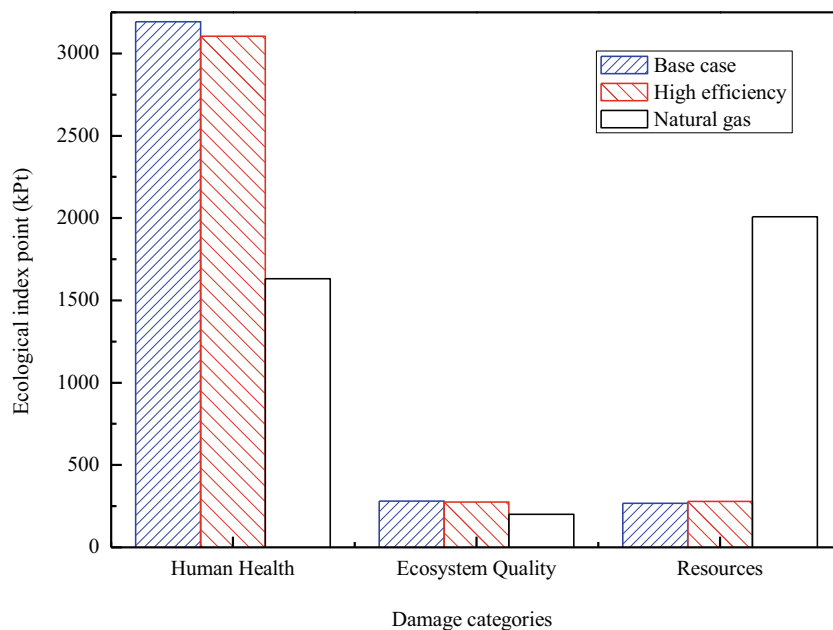
Table 3 The inventory of system using natural gas scenario

Step	Unit	Value	Materials and energy	Data sources ^a
Devulcanization				
Input	MJ	90,000,000	Natural gas	(1)
Output	kg	6.44	SO ₂	(3)
	t	3.01	NO _x	(3)
	t	3,035.8	CO ₂	(3)

^a The numbers refer to the five sources mentioned in the above in Sect. 2.4

Moreover, when focusing on energy input instead of waste emission, reference scenario 2 is studied by investigating the effect of using natural gas as a coal alternative. The inventory data of the system using natural gas is listed in Table 3.

The results are compared with the base case scenario, as shown in Figs. 5 and 6 at impact category level and damage category level, respectively. At impact category level, reference scenario 1 has an environmental impact reduction by −2.1 % due to the reduction of NO_x and SO₂. The major reduction is on respiratory inorganic while an increase has

Fig. 5 Comparing of three scenarios at impact category level**Fig. 6** Comparing of three scenarios at damage category level

been found on carcinogens and land use owing to more material input. Compared with base case scenario, environmental impact of reference scenario 2 is largely reduced by –21.5 % on respiratory inorganic, categories, and climate change, mainly due to the utilization of cleaner fuel. However, there is huge impact increase on fossil fuels, turning into the dominant impact. The significant increase in fossil fuels category is mainly due to the surplus energy needed for future extractions of natural gas. At damage category level, both of the reference scenarios show a reduced harmful impact on human health and ecosystem quality and an increasing impact on resources, especially the natural gas scenario.

As a conclusion, when coal is replaced by natural gas to generate equivalent energy, the environmental load can be efficiently decreased, especially on respiratory inorganic and human healthy. However, employment of a more advanced gas treatment technology does not show significant improvement on reducing environmental load of the ground rubber production process. The result proved that the utilization of cleaner energy is a more efficient and promising way to reduce the adverse environmental impacts.

Moreover, electricity mix in China mainly consisted of coal firing that accounts for 80 %, indicating that the electricity applied in the system also comes from coal combustion. It can be concluded that improvement of power efficiency will further reduce the environmental load in this process. For example, current system consisted of three steps. In the first step, a battery of machines is used to produce rubber powder from recycled tires, resulting in huge electricity consumption. The technology of internal mixer (Yu 2010) combines the unit process of grinding into devulcanization stage. Meanwhile, the unit process of screening is not required anymore. According to the clean production standard of Chinese reclaimed rubber industry, the technology of internal mixer generally reduces electricity consumption significantly (Liu et al. 2012). Hence, utilization of energy-saving equipment, such as internal mixer, might be an efficient approach to reduce environmental impacts.

4 Conclusions

The four questions raised in the end of section 1 are answered below:

- (1) During ground rubber production process, it causes the most significant adverse effect in the respiratory inorganic category, mainly due to the emission from coal combustion;
- (2) The step of devulcanization owns the highest environmental load of about 66.2 % mainly due to the large amount of coal burned for extensive energy consumption

in this step. Refining poses the second highest environmental load of 29.7 %, which is mainly from electricity consumption. Rubber powder preparation is the lowest environmental load of about 8.06 %;

- (3) At damage category level, human health is the dominant damage category in the life cycle of ground rubber production.
- (4) Improvement on the flue gas treatment can contribute to a cleaner production and a more environmental-friendly process. When coal is replaced by natural gas to generate equivalent energy, the environmental load can be more efficiently decreased. Moreover, utilization of energy-saving equipment, such as internal mixer, might be an efficient approach to reduce environmental impacts.

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